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EXPERIMENTAL AND MODEL TRANSPORT AND DIFFUSION STUDIES IN COMPLEX TERRAIN WITH EMPHASIS ON TRACER STUDIES

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ABSTRACT

The U.S. Department of Energy (DOE) Atmospheric Studies in Complex Terrain (ASCOT) program began in the fall of 1978 as a multiple DOE and other Federal Laboratory program devoted to developing a better physical understanding of atmospheric boundary layer flows in areas of complex terrain. The first technical challenge undertaken by the program was an investigation of atmospheric boundary layer phenomena associated with the development, continuation and breakup of nocturnal drainage wind flows. This paper discusses the general objectives the program has addressed during the past several years and focuses on results from a major field experiment conducted in 1980 in The Geysers area of northern California. Specifically, results from measurements of simultaneous tracer releases are compared to calculations from a mass-consistent wind field model coupled to a particle-in-cell transport and diffusion model. Results of these comparisons show that model calculations agree with measurements within a factor of 5 approximately 50 percent of the time. Part of the difficulty faced by the models in these comparison studies is associated with large variabilities between measurements made by samplers located one or two Δx apart when compared to the resolution of the models. Space and time averaging improves the comparisons considerably, although the design of the field experiment did not allow the determination of optimum spacial and temporal averages.

INTRODUCTION

The Department of Energy is currently sponsoring a program of Atmospheric Studies in Complex Terrain (ASCOT) to improve the technology needed to assess air quality impacts of developing energy resources in areas of complex terrain. The program uses field experiments, theoretical atmospheric physics research, and mathematical models to develop a measurements and modeling methodology that can provide quality assessments in these areas. The ASCOT team is composed of scientists from several DOE-supported research laboratories and university programs.

With the program's initial focus on studying transport and dispersion of materials injected in or near nocturnal drainage flows, three series of field experiments were conducted in The Geysers geothermal area in northern California. The initial experimental series, conducted during July 1979 in the Anderson Creek valley of The Geysers area, were exploratory in nature and of limited scope. Results from this series of experiments were used to plan a second series of experiments during September 1980 in the same valley, to acquire more detailed information about the temporal and spatial characteristics of drainage flows and their interaction with the regional and synoptic scale flows. In contrast to these generic studies of the transport and dispersion of pollutants entrained in drainage flows, a third series of experiments, conducted during August 1981 in the Big Sulfur Creek valley of The Geysers, was designed to (1) acquire data needed to predict the impact of the hydrogen sulfide emissions from future geothermal power plant cooling tower plumes during nocturnal drainage flows, and (2) to perform nocturnal drainage flow studies in a different environmental setting for testing the general applicability of the methodologies developed from the experimental studies in the Anderson Creek valley (Dickerson and Gudiksen, 1984; Gudiksen and Dickerson, 1984). This paper concentrates on the 1980 field studies, particularly on the tracer experiments. The variability between concentration values measured by closely spaced samplers is discussed and the relationship between measured and modeled concentrations is described.

EXPERIMENTAL DESIGN

With the goal of studying the transport and dispersion of materials injected in or near drainage flows, the design of the experiments reflected the following general evaluations:

- the entire nocturnal drainage cycle from initiation to full development and breakdown.
- the temporal and spatial characteristics of the drainage flows within the valley, including the evolution of pooling of drainage flows within the Anderson Creek valley and the subsequent outflow of this air from the valley.
- the influence and the extent of mixing between the external flows and the drainage flows within the valley, and
- the effect on the drainage flows of changing surface roughness due to forest canopies.

The 1980 series of experiments, in the Anderson Creek valley, consisted of five identical experimental plans conducted on different but similiar nights. Each experiment consisted of tracer studies coordinated with a host of meteorological studies. The Anderson Creek valley has the characteristics of a basin. Its topographic features and the layout of the tracer studies are shown in Fig. 1. The valley is bounded by Cobb Mountain to the north, by a ridge to the west and south, and by Boggs Mountain to the east. The Anderson, Gunning, and Putah Creeks, which form the principal drainage areas, merge near Anderson Springs with outflow toward the southeast. The tracer studies included the use of two perfluorocarbons, two heavy methanes, and sulfur hexafluoride gases that were measured using conventional sampling techniques. Also oil fog tracked by lidar and tetroons tracked by radar were used in these experiments. One of the perfluorocarbon tracers (PMCH; C_7F_{14}) was released into the nocturnal drainage flows from an open, but very sheltered area in Anderson Creek; the other perfluorocarbon tracer (PDCH; C_8F_{16}) was released within a forest canopy in Gunning Creek. These sites are located approximately halfway between the floor of the valley and the top of the ridge. Two heavy methane tracers, methane-20 ($^{12}CD_4$) and methane-21 ($^{13}CD_4$) were released within the upper reaches of the Anderson Creek drainage area. The methane-21 was released at the surface directly into the drainage flows; methane-20 was released simultaneously into the transition layer at a height of 60 to 75 m above the surface to investigate the extent of mixing between the transition layer flows and the drainage layer. The sulfur hexafluoride was released in the upper part of the Putah Creek drainage area to evaluate the merging of the flows from Putah Creek with those from the Anderson and Gunning Creek drainage areas. All of the releases were one hour in duration. The downwind surface concentrations were sampled at 30 to 50 locations depending upon the tracer. The sampling periods ranged from 10 minutes

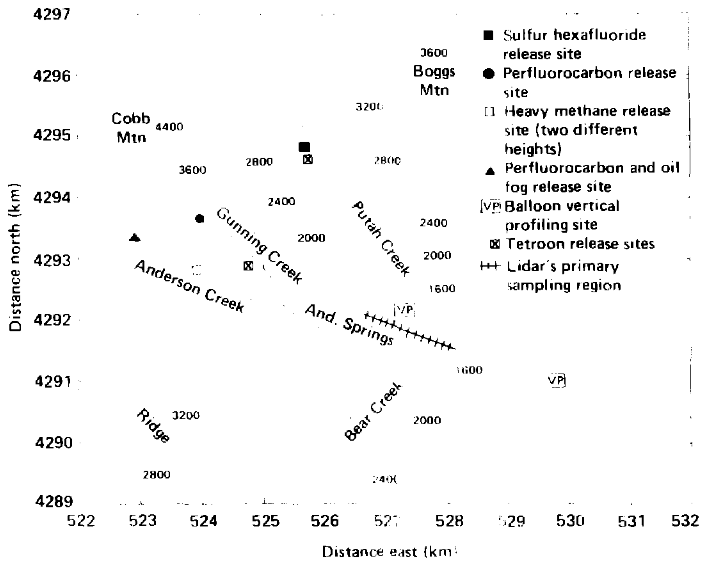

Figure 1. Layout of the ASCOT tracer experiments conducted within the Anderson Springs Valley in 1980.

to 8 hours. In addition, two vertical profiling systems were used to define the temporal variations in the vertical distributions of the tracers within the valley basin and outflow region. These consisted of balloon borne sampling systems. The sampling and analytical techniques for the perfluorocarbon tracers have been reported by Ferber et al. (1981) and by Lovelock and Ferber (1982), while those for the heavy methane tracers have been reported by Cowan et al. (1976) and Fowler (1979).

To acquire more detailed structural information about the three-dimensional evolution of these tracers, oil fog was released at the same site as the PMCH perfluorocarbon tracer and tracked by a lidar. For each release, the lidar, situated near the valley outflow region, performed a series of scans in various vertical planes to observe the evolution of the plume. The region most frequently sampled by the lidar and, hence, the site of the most detailed analyses is shown in Fig. 1. The lidar used in this work has been described by Eberhard (1981). The remaining tracer studies were tetroons tracked by radar within the Anderson and Putah Creek drainage areas. These were released at a height of 100m both individually and in clusters of three from the two sites shown in Fig. 1. Thus, the tetroons were flown in the transition layer overlying the drainage flows within the two valleys, and provided direct measurements of individual air parcel trajectories and dispersion characteristics of these air parcels. A description of the radar and the data analysis techniques is reported by Fosberg and Lanham (1983).

Meteorological measurement systems dedicated to these experiments included an array of nine acoustic sounders, seven tethersondes, eight optical cross-wind anemometers, two rawinsondes, one minisonde, 27 surface meteorological stations with real-time telemetry, as well as ten 10 m and one 60 m meteorological towers. Most of the acoustic sounders, tethersondes, and optical anemometers were dedicated to evaluating characteristics of the drainage flows within the three major drainage areas and for evaluating interactions of these flows with the transition layer flows and the pooling within the valley basin. The surface stations, on the other hand, provided a comprehensive view of the surface flow characteristics over the entire valley. Finally, the rawinsondes and the minisonde, which were located outside the valley, were dedicated to defining the regional scale flow within which the Anderson Creek valley was imbedded. The complete data set for these experiments has been reported by Gudiksen (1983). A more complete description of the experimental plan has been reported by Dickerson (1980).

TRACER AND MODELING STUDIES

The surface distributions of the PMCH and PDCH tracers, released for a one-hour period within the Anderson Creek and Gunning Creek drainage areas, are shown in Fig. 2 for the first two hour period

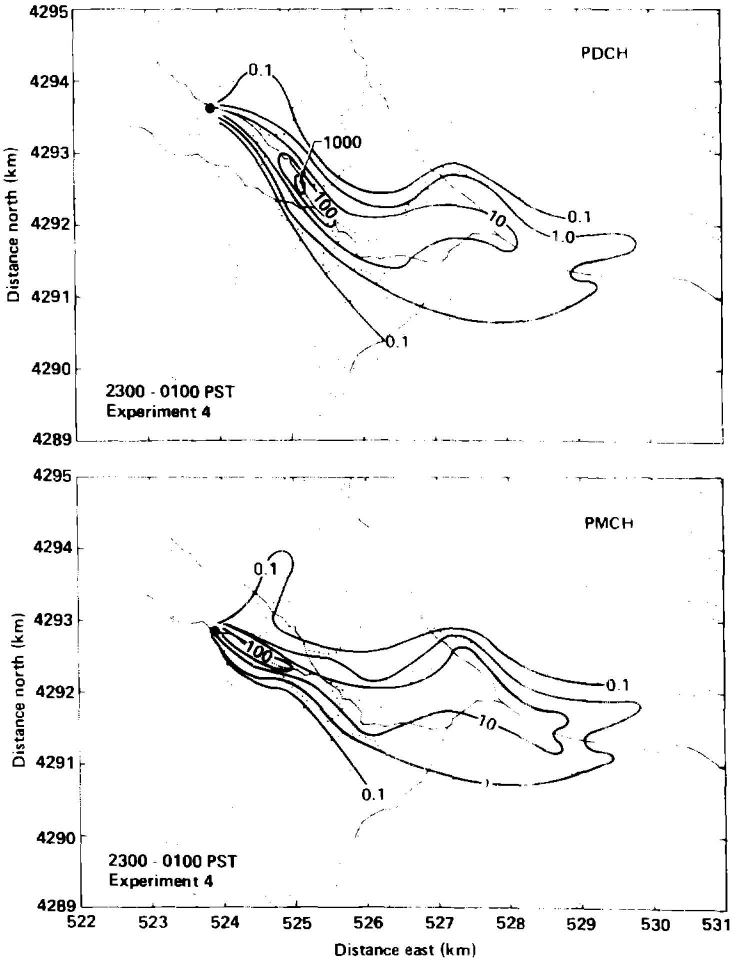

Figure 2. Surface concentration patterns of PDCH (top) and PMCH (bottom) during Experiment 4. Units are ppt and are averaged over the first 2 hours after initiation of the release.

after the initiation of the release. This figure illustrates a typical (smoothed) pattern seen for the perfluorocarbon releases during the 5 experiments. A complete summary of the experiments has been reported by Gudiksen, et al. (1983).

Results from these experiments and the SF_6 and heavy methane releases have been utilized to evaluate a three-dimensional mass-consistent diagnostic wind field model (MATHEW) and a particle-in-cell transport and diffusion model (ADPIC) for simulating pollutant behavior in drainage flows. These models have been described by Sherman (1978) and Lange (1978). MATHEW provides ADPIC with hourly averaged wind fields which are used to compute pollutant transport by the mean winds. ADPIC computes diffusion velocities based on empirically-determined eddy viscosity coefficients and the pollutant concentration gradients. The pollutant is represented by a large number of Lagrangian "marker" particles which are transported by the combined mean and turbulent velocities. The pollutant concentrations are obtained by counting the particles within each grid cell.

To date, the models have been run using the data from Experiments 2 and 4 of the September 1980 series in the Anderson Creek valley. For this study, the calculational domain was 7 by 10 km extending 1100 m above the lowest point in the topography. Individual cells were 250 by 250 by 50 m in the x, y and z directions, respectively. Using the hourly averaged meteorological data from the surface stations, tethersondes, and acoustic sounders, the models computed the concentration distributions of all the gaseous tracers utilized in this experiment. As an example of the results, Fig. 3 shows the computed surface concentration pattern of the PDCH tracer released within the Gunning Creek drainage area. This pattern may be compared directly with the measured distribution shown at the top of Fig. 2. Generally, results of the calculations agree reasonably well with the observed concentration patterns. Ratios of measured to computed concentrations for Experiments 2 and 4 were within a factor of 5 for 40 to 60 percent of the samples as shown in Fig. 4. However, agreement within a factor of two occurred over a range of 12 to 32 percent of the samples.

Previous model comparison studies with measured concentration data are summarized and shown by the curve in the upper left corner of Fig. 4. These studies were conducted in areas with rolling terrain considerably less complex than the Geysers area. For these studies the ratios of measured to computed concentration values by the MATHEW/ADPIC models were within a factor of 2 about 60% and a factor of 5 about 80% of the time. Thus, complexities introduced by the rough

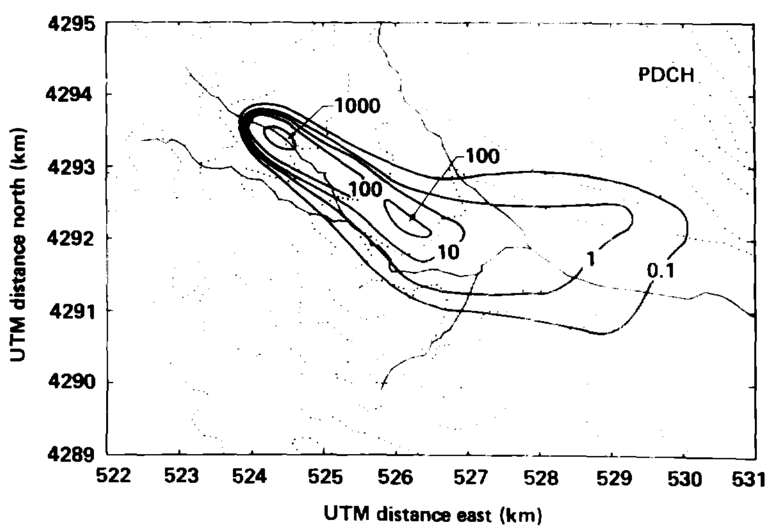

Figure 3. MATHEW/ADPIC calculated concentration pattern of PDCH during Experiment 4.

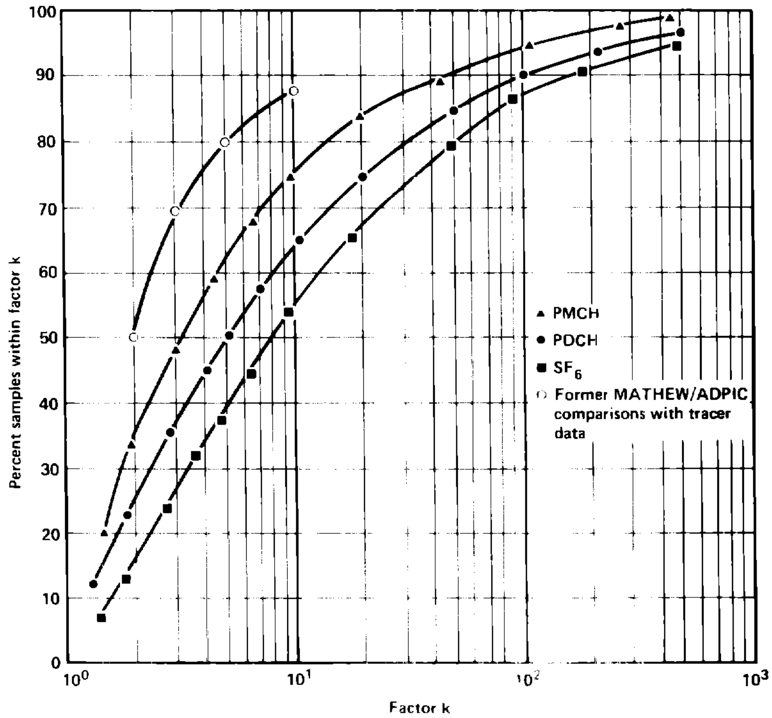

Figure 4. Percent of MATHEW/ADPIC calculations within a factor k of measurements.

terrain coupled with the nighttime stable boundary layer tended to noticibly degrade the comparisons.

Variability of Tracer Concentration Measurements

One aspect of transport and dispersion characteristics expected to emerge from a stable boundary layer coupled to complex terrain is the variability in both space and time of measured tracer concentration values, even if the samplers are relatively closely spaced. Although the 1980 Geysers tracer releases were not designed for such a study, three groupings (clusters) of samplers provided an opportunity to investigate the variability of tracer measurements made at samplers located from 0.9 to approximately 6.0 km from the release points. Spacing between these clustered samplers ranged from 100 to 600 m. Fig. 5 shows the relationship of the 3 sampler clusters (C1, C2, C3) chosen for this study to the tracer release points for PMCH, PDCH and SF_6. Table 1 lists average spacing of samplers within each cluster and the average distance from each cluster to the respective tracer release points. Contour intervals shown in the enlargements are 25 m. For purposes of comparison with Gaussian diffusion estimates, σ_y is shown for a stable atmosphere (that includes meander) for distances downwind equal to the distance of the cluster locations from the tracer release points. The maximum difference in elevation between samplers within a cluster is also given in Table 1.

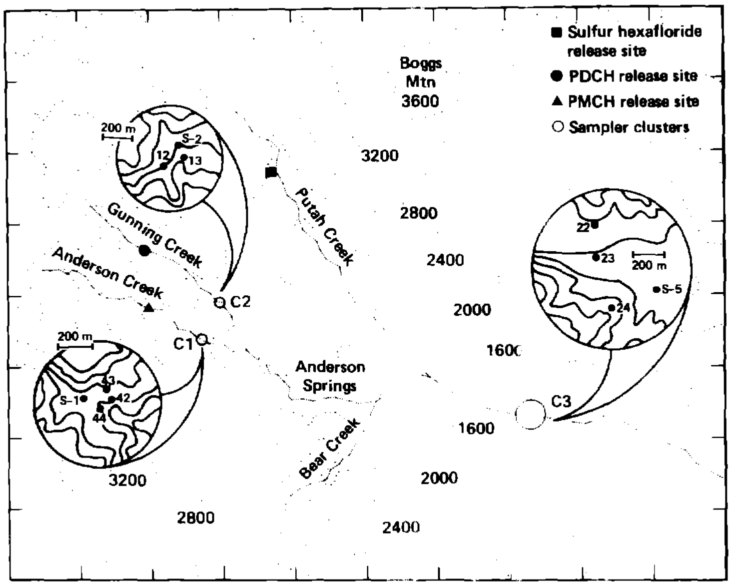

Figure 5. Location of sampler clusters.

Table 1. Relationships of samplers within the clusters and distance of the clusters from the release points.

Cluster #	Average distance from tracer release points (km)			Average distance between samplers (m)	σ_y (m)	Maximum difference in elevation between samplers (m)
	PMCH	PDCH	SF_6			
C1	0.9	--	--	150	120	12
C2	--	1.4	--	150	150	20
C3	5.9	5.9	6.0	440	650	40

For the first four experiments ratios between equivalent two hour average concentration measurements were calculated for every pair of samplers within each cluster. These ratios were expressed as factors for C1 (PMCH), C2 (PDCH) and for the three tracers measured in C3 (PMCH, PDCH, SF_6). Figure 6 shows the results of these comparisons where numbers in parentheses above each column of points indicates the number of comparisons for each group. Results depicted in Fig. 6 show that the variation among sampler values increases with distance from the tracer release points from almost an order of magnitude to about two orders of magnitude (with the exception of one point in C3). Normally a greater variation is expected near the tracer release points since the concentration pattern is not as diffuse and is therefore subject to larger concentration gradients.

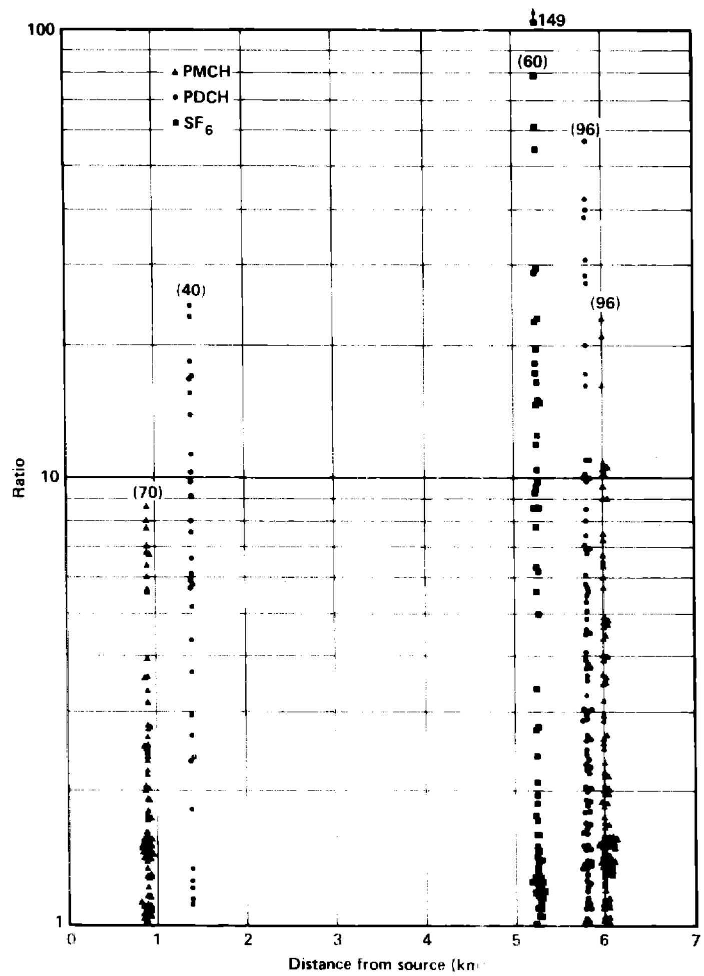

Figure 6. Ratios of 2 hour average concentration measurements within each sampler cluster.

To further illustrate the variation ratios for each 2 hourly concentration measurement to the lowest 2 hourly value measured within a cluster were calculated. Four 2 hourly sets of ratios were produced for each tracer for each experimental. Nightly 8 hour average concentration values and ratios were also calculated, as well as 32 hour averages and ratios for the combined four experiments. Results of these calculations, depicted as the maximum variation between sampler values within a cluster for the 2, 8 and 32 hourly averages are shown in Fig. 7 for C1 and C2. For C1, during the first experiment, variations between the four samplers ranged from about 1.2 to 8 and variations of sampler values in C2 ranged from 17 to 21. With the exception of experiment 3, sampler values in C2 varied by almost an order of magnitude over values in C1. Nightly 8 hour ratios were less than the 2 hour ratios for C1 except for experiment 1. In this case the largest 2 hr ratio occurred during a period that highest concentrations

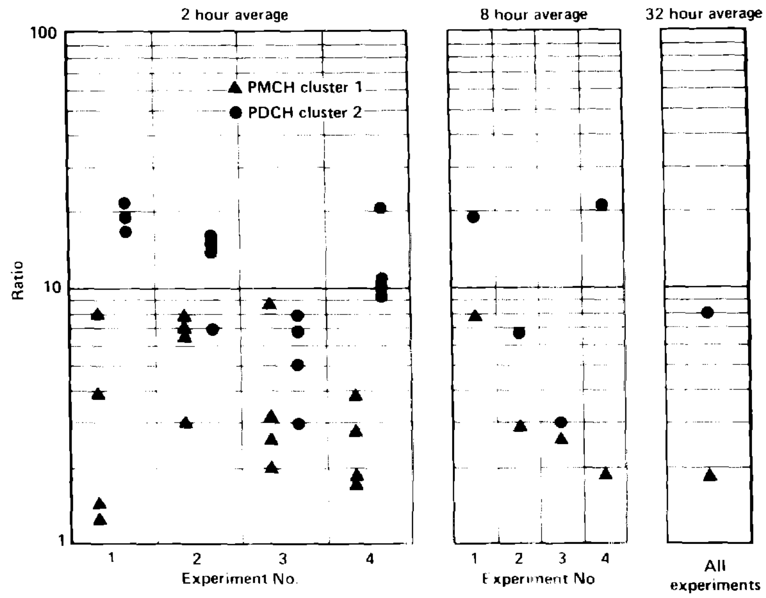

Figure 7. Ratios of sampler measurements in clusters 1 and 2 for 2, 8 and 32 hour averages.

(which could range over several orders of magnitude during the night) were measured. This is the reason that, with the exception of experiment 3, averaging did not significantly improve the ratios in C2. Experiment 3, which was not subject to strong drainage winds is a special case and will be discussed later in this report. Variations between sampler values averaged over the four experiments (32 hours) reduced to less than a factor of 2 for C1 but were a factor of 8 for C2. This points to a systematic bias in the sampler locations chosen to represent C2 although the samplers were relatively closely spaced.

Figure 8 shows comparisons of ratios for concentrations measured in C3 for the three tracers. Again the large variation (generally factors of 10 to 40) between concentration values measured by samplers located relatively close to each other (440m average for C3) is striking, particularly since the cluster is from 5.25 to approximately 6 km from the tracer release points. PMCH, released in Anderson Creek, shows the least variation for 2 hour averages and SF_6 released in Putah Creek shows the greatest variability except for experiment 3. Averaging over each night (8 hours) reduced the maximum ratios by a factor of 5 to 10 with minimal additional reduction gained by averaging over the four experimental nights.

It is difficult to determine specific reasons for the observed variations between sampler values within the clusters chosen for this study; however, it is apparent that both a systematic and a random component exists. In most cases temporal averaging for 8 hours reduced the ratios, with a slight additional reduction gained by averaging

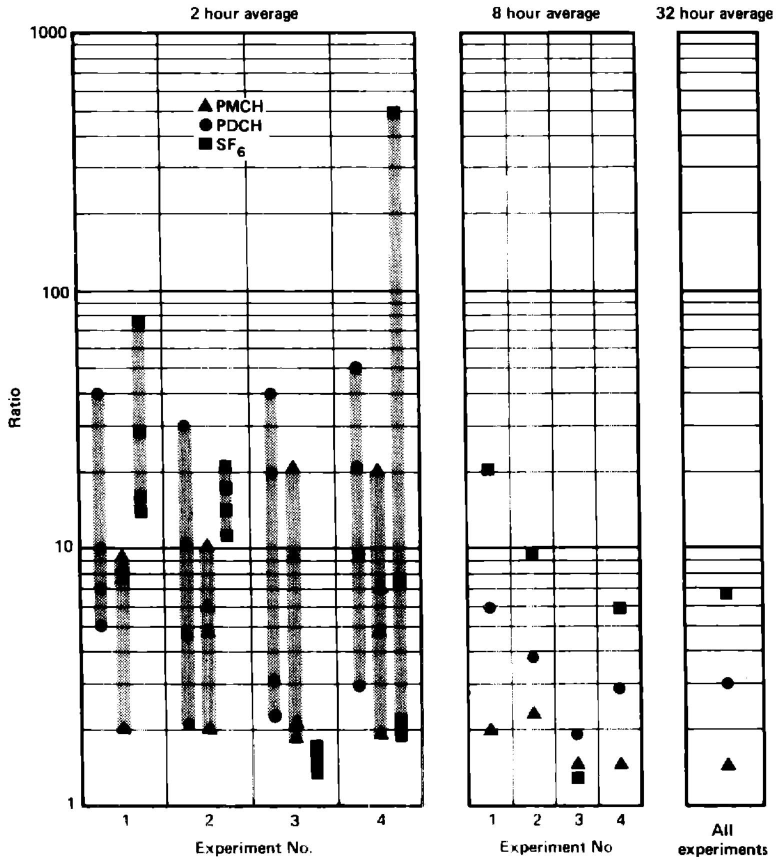

Figure 8. Ratios of sampler measurements in cluster 3 for 2, 8 and 32 hour averages.

over the four experiments. The natural variability associated with the transport and diffusion processes is expected to be a random component and should diminish with averaging. The systematic component (which contributes to the representativeness of the measurements) is attributed to a combination of the complex meteorological processes involved, caused in this case by a stable nighttime boundary layer coupled with underlying complex terrain. Although the samplers in each cluster were closely spaced, small differences in elevation or surrounding terrain features can significantly influence concentration patterns developed under stable atmospheric conditions. As constant density layers develop and flow over one another the lowest layers are influenced and guided by the terrain features. For example, there is evidence from the tracer concentration pattern analysis that the flow near C3 favored the north side of the outflow region as the flow exits the valley. This feature of the flow is observed in the low concentrations consistently measured by Sampler 24. Samplers 22 and S-5 (in the floor of the valley) were the remaining samplers that occassionally reported the lowest 2 hour average concentration measurements.

Although less than 60 m from sampler 13, Sampler 12 in C2 consistently measured lower values by an order of magnitude or greater. In this case sampler 13 and S-2 were probably located in the drainage layer flowing down Gunning Creek and sampler 12 was either shielded from the drainage flow by terrain features or was above the drainage layer. On the other hand all the samplers located in C1 appear to be located in the drainage flow down Anderson Creek since the maximum ratios shown in Figure 7 reduce to factors of 2 or 3 for 8 hour averages.

During experiment 3 the general meteorological conditions were not favorable for strong drainage wind development which resulted in weak drainage winds developing several hours after the tracers were released. Comparisons of 2 hour ratios between samplers shown in Figures 7 and 8 for experiment 3 show values similiar to the other nights for PDCH and PMCH while being less than a factor of 2 for SF_6. When the concentration values were averaged for 8 hours the maximum ratios reduced to less than a factor of 3 for all tracers measured in the three clusters. The major reason attributed to this reduction was the development of a weak drainage layer influenced by relatively strong ($\sim$8 m/s) upper level winds that existed during experiment 3.

Variability of Model Calculations

The large variability that can exist between average concentration values measured at samplers located relatively close to each other poses a difficult problem for comparing calculated model point values to individual sampler point values. One question that immediately surfaces is, can the model produce similar variabilities at these sampler locations? Samplers in cluster 3 were chosen for comparison with model calculations using the first six hours (three 2 hourly averages) for experiments 2 and 4. Results of these calculations and their associated variabilities were compared to equivalent measurements (Fig. 9). The most surprising element shown in this figure is the large variability shown by the model calculations. Resolution of the model was 250 m compared to the average spacing of 440 m for the sampler locations.

Although model calculations and measurements show equivalent variabilities, comparisons between individual 2 hourly average values differed by more than an order of magnitude. Similiar variabilities between model calculations and measurements are also shown for 6 hour and 12 hour averaging times. Elements in the MATHEW/ADPIC model that contribute to the observed variability in the calculated concentration values are the model terrain and hourly changing wind field. When the measurements and calculated values were spacially averaged over the cluster and temporally averaged for 6 hours for each experiment there was good agreement between the model calculations and measurements (Table 2). With the exception of PDCH for Experiment 2 the comparisons were well within a factor of 2.

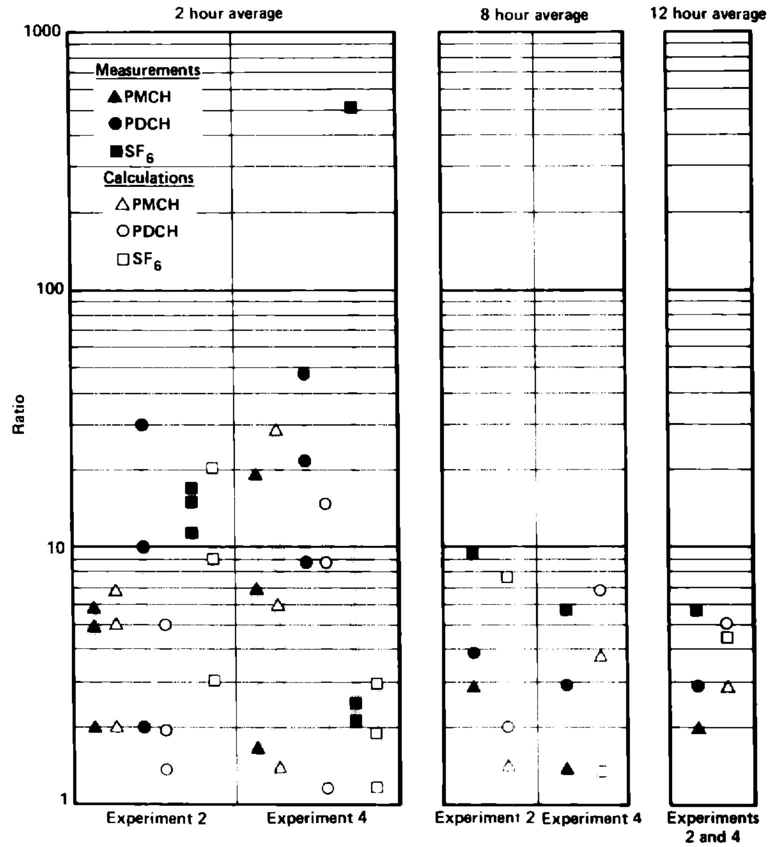

Figure 9. Ratios of sampler measurements compared with ratios of model calculations in cluster 3.

Table 2. Comparison of measured and calculated six hourly concentration values averaged over samplers in cluster 3.

Experiment	Tracer	Measured	Calculated
2	PMCH	4.3	2.5
	PDCH	6.6	0.7
	SF_6	161.0	134.0
4	PMCH	5.1	9.8
	PDCH	8.0	6.6
	SF_6	35.0	38.5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The ASCOT 1980 field experiments in The Geysers area of northern California have been briefly described and the measurements have been used to investigate the spacial variability that exists between concentration measurements made at samplers located relatively close to each other. Examples, using samplers in three clusters, showed variations of more than an order of magnitude for 2 hour average concentrations measured, in some cases, few tens of meters apart and within a kilometer of the tracer release points. These large variations, expressed as ratios to the smallest measured value, persisted and in some cases were larger for samplers located up to 6 km from the tracer release points and spaced a few hundred meters apart. Averaging concentration values for 8 hours tended to reduce the ratios; however, averages over the four experiments produced only a slight additional reduction. For one experiment, when weak drainage winds existed in the lower boundary layer and stratified drainage flows did not fully develop, ratios of 8 hour average concentrations values were less than a factor of 3 for measurements in all three clusters.

A systematic and a random component of the variation between sampler values is suggested to separate the natural variability of the atmosphere from the influence of the measurement environment. Although the ASCOT experiments were not designed to determine these components, there is evidence from this study that the systematic component can be large between relatively closely-spaced samplers. The combination of complex terrain, coupled with a stratified lower boundary layer, appears to contribute significantly to the observed systematic differences between samplers.

Model calculations for two experiments showed the same order of magnitude variability between sampler locations for 2, 6, and 12 hour averages. This model variability was surprising since the model resolution was either less than or slightly greater than the spacing between samplers. The major contributors to the variability in the model calculations were attributed to the hourly changing windfields developed from measurements and the terrain modeled as building blocks. Although comparisons between individual 2 hour measurements and model calculated values varied over an order of magnitude, they agreed for two experiments within less than a factor of 2 when the measurements and calculations were averaged over space and time for each cluster for each experimental night.

Several implications are suggested by this study for making measurements of tracer or pollutant concentrations in complex terrain, particularly under nighttime drainage wind conditions. For example, care should be exercised in the placement of air quality monitoring stations in areas subject to these conditions. Comparisons of ratios measured by samplers in C3 showed that the variations are more a function of sampler placement than of tracer release points. Even 8 and 32 hour average concentration measurements made by closely spaced samplers can vary by an order of magnitude.

Spatially averaging meteorological data by remote sensing instrumentation has been shown to be effective for developing model input data and model testing (Porch and Lange, 1982). Comparison of the temporal spectrum of optical cross-wind sensors over paths ranging from a few hundred meters to several kilometers with tower mounted anemometers shows that averaging times greater than 1-2 hours are required at a point in complex terrain to produce variability similiar to that found in spatially averaged data over a few hundred meters. This increased variability in meteorological flow fields induced by complex terrain is reflected in the tracer variability. Since the spatial averaging feature of optical cross-wind sensors has helped to quantify the variability in the flow fields in complex terrain and provided data more compatible with the spatial scales of numerical models, a possible deployment of double-ended spectrographic systems for spatially averaged tracer concentrations should be explored. Laser or incoherent light detection systems for wavelengths affected and unaffected by tracer material should be developed and applied to quantifying the spatial variability of tracers in complex terrain, as well as providing improved input for numerical model evaluation.

To provide additional insight into the space and time variability expected in measurements due to both the underlying terrain and the associated meteorology an experimental design is suggested that uses clusters of tracer samplers along with the associated meteorological instrumentation. This is a different approach to the standard methods of arcs or random spacings for sampler placement which intercept the tracer material. Optimum spacing among samplers within a cluster and spacing between clusters can be determined by a combination of modeling and statistical studies. In addition, remote sensing instrumentation can be included to determine temporal and spacial relationships between point and space averaged measurements. These experiments can be designed and conducted in complex as well as simple terrain. Examples of objectives for a set of experiments designed in this manner are:

- Determination of systematic variations induced in concentration measurements by complex terrain.
- Determination of optimum spacial and temporal averages of concentration measurements for estimating representative measurements for model evaluation studies.
- Development of guidelines for locating air quality measurement stations in complex terrain.

Although a number of experiments would be required in both the simple and complex terrain areas, an initial set of experiments in each setting would help establish guidelines outlined by the above objectives and provide a framework for developing an understanding of the increased complexities introduced by the atmospheric boundary layer when it comes in contact with complex terrain.

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